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Saccadic Targeting Deficits in Reading among Children with Developmental Dyslexia: Experimental Evidence from Novel Word Learning

Authors: Liang Feifei, Ma Jie, Li Xin, Lian Kunyu, Tan Ke, BAI Xuejun, Bai Xuejun

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Abstract

By comparing the similarities and differences in changes to saccade positioning patterns during repeated new word learning with chronological age-matched children, this study investigated whether children with developmental dyslexia exhibit deficits in saccade positioning during new word learning. Using children with developmental dyslexia and chronological age-matched children as participants and employing a repeated new word learning paradigm, the results revealed: (1) Compared with the chronological age-matched group, children with developmental dyslexia demonstrated shorter saccade amplitudes when launching into new words, and the initial fixation landing position during multiple fixations was closer to the word beginning; (2) Children in the chronological age-matched group showed greater ability than children with developmental dyslexia to modulate saccade positioning patterns for new words based on learning exposures, that is, as the number of new word learning exposures increased, the saccade amplitudes for both launching into and exiting from new words in the chronological age-matched group increased accordingly, and the initial fixation landing position shifted closer to the word center; in contrast, children with developmental dyslexia exhibited increases only in saccade amplitude when exiting new words, with the magnitude of increase also being significantly smaller than that of the chronological age-matched group. The results indicate that children with developmental dyslexia manifest deficits in both saccade positioning during new word learning and the modulation of saccade positioning utilizing learning exposures.

Full Text

Saccadic Targeting Deficits in Children with Developmental Dyslexia During Reading: Evidence from Novel Word Learning

LIANG Feifei[1], MA Jie[2], LI Xin[2], LIAN Kunyu[2], TAN Ke[2], BAI Xuejun[1],[2] [1] School of Education and Science, Tianjin Normal University, Tianjin 300387, China [2] Academy of Psychology and Behavior, Tianjin Normal University, Tianjin 300074, China

Abstract

This study investigated whether children with developmental dyslexia exhibit deficits in saccadic targeting during novel word learning by comparing their eye movement patterns with those of chronological age-matched controls during repeated exposure to new words. Using a novel word learning paradigm with repeated exposures, we found that: (1) Compared to the age-matched group, children with developmental dyslexia showed shorter incoming saccade lengths to novel words and initial fixation positions in multiple-fixation cases that landed closer to the word beginning; (2) Age-matched children demonstrated greater ability to modulate saccadic targeting patterns using learning trials than children with developmental dyslexia. Specifically, as learning trials increased, age-matched children showed increased incoming and outgoing saccade lengths to/from novel words and initial fixation positions that shifted closer to the word center. In contrast, children with developmental dyslexia only showed increased outgoing saccade lengths, and this increase was significantly smaller than that of the age-matched group. These results indicate that children with developmental dyslexia exhibit deficits both in saccadic targeting during novel word learning and in using learning trials to modulate such targeting.

Keywords: developmental dyslexia; novel word learning; saccadic targeting; Chinese reading

1. Introduction

Children with developmental dyslexia (DD) typically demonstrate significantly smaller vocabularies compared to their typically developing peers (Bai, Zhang, Meng, Tan, & Wang, 2018; Guo, Tan, Song, Peng, & Bai, 2018; Li et al., 2019; Meng, Cheng-Lai, Zeng, Stein, & Zhou, 2011; Shu, McBride-Chang, Wu, & Liu, 2006; Zhang, Xie, Xu, & Meng, 2018). During elementary school, one primary mechanism for vocabulary acquisition is incidental learning from reading contexts (Liang, Zhang, Zhang, Wang, & Bai, 2017; Nagy & Scott, 2000). Consequently, examining the efficiency of novel word learning during reading has become a central issue in dyslexia research. Early studies primarily relied on subjective self-report measures to assess novel word learning efficiency during reading (Kuhn & Stahl, 1998).

The application of eye-tracking technology in this domain has enabled researchers to simultaneously investigate the underlying cognitive processes of novel word learning from both temporal ("when" to move the eyes) and spatial ("where" to move the eyes) perspectives (Liang, Wang, Zhang, Yan, & Bai, 2016; Wang, Chen, Zhao, Li, & Bai, 2017; Blythe et al., 2012; Chaffin, Morris, & Seely, 2001; Joseph & Nation, 2018; Joseph, Wonnacott, Forbes, & Nation, 2014; Liang et al., 2017; Liang et al., 2015; Lowell & Morris, 2014; Weighall, Henderson, Barr, Cairney, & Gaskell, 2017). Previous research from the temporal perspective has revealed that children with DD exhibit atypical patterns of fixation duration changes during novel word learning, requiring more contextual exposures to show significant decreases in first fixation duration and gaze duration, and demonstrating slower reductions in total fixation time —indicating impaired novel word learning abilities during reading (Bai et al., 2019).

Given that "when"(reflecting processing duration) and "where"(reflecting landing position efficiency) represent two independent subsystems of oculomotor control in reading that show differential developmental trajectories (Blythe & Joseph, 2011; Reichle et al., 2013), with "when" being primarily influenced by higher-level linguistic features and developing toward adult levels around age 7 as language skills improve (Blythe & Joseph, 2011), a critical question remains: Does the impaired novel word learning efficiency in children with DD stem solely from deficits in the temporal domain, or do spatial deficits also contribute? Clarifying the saccadic targeting patterns of Chinese children with DD during novel word learning is essential for constructing oculomotor control models of lexical acquisition and for identifying potential intervention strategies.

Current evidence regarding whether Chinese children with DD exhibit saccadic targeting deficits during reading remains inconclusive. Bai et al. (2011) compared saccadic targeting among Chinese children with DD, chronological age-matched controls, and reading ability-matched controls. Using the data processing method of Yan, Kliegl, Richter, Nuthmann, and Shu (2010), they categorized initial fixation position data into single-fixation cases (exactly one fixation during first-pass reading) and multiple-fixation cases (two or more fixations during first-pass reading). The results revealed similar targeting patterns across all three groups: in single-fixation cases, all children tended to fixate near the center of two-character words, while in multiple-fixation cases, all children tended to land their initial fixations on the word beginning.

However, subsequent research has questioned this separate statistical approach (Li, Liu, & Rayner, 2011), arguing that regardless of readers' oculomotor control strategies—even when employing constant saccade length strategies (Li et al., 2011)—if the initial landing position falls near the word center, the probability of the next saccade exiting the word is inherently higher than if the initial landing position falls on the word beginning. Therefore, whether Chinese children with DD exhibit saccadic targeting deficits during reading requires further investigation.

Novel word learning presents unique challenges for saccadic targeting compared to reading familiar words. First, research has consistently shown that word frequency significantly influences saccadic targeting: compared to high-frequency words, low-frequency words elicit shorter incoming saccades, initial fixation positions closer to word beginnings, and shorter outgoing saccades (Liu, Reichle, & Li, 2015, 2016; Liu, Huang, Li, & Gao, 2017). Novel words resemble extremely low-frequency items (Blythe et al., 2012; Chu & Leung, 2005), suggesting that readers may experience particular difficulty in targeting saccades during novel word learning. Second, during novel word learning, readers lack top-down lexical representations and must rely exclusively on bottom-up processing for word identification. This process involves first obtaining partial information about the novel word (such as orthographic and phonological features) through parafoveal preview (Pollatsek, Tan, & Rayner, 2000; Yan, Richter, Shu, & Kliegl, 2009), followed by foveal lexical access. Research indicates that children with DD have reduced perceptual spans during reading (Xiong, 2014) and exhibit deficits in orthographic, phonological, and morphological processing (Ho, Chan, Tsang, & Lee, 2002; Ho, Law, & Ng, 2000; Shu et al., 2006). Consequently, we hypothesize that children with DD may experience greater difficulty with parafoveal preview of novel words, potentially impairing their saccadic targeting. Therefore, our first objective was to investigate whether children with DD demonstrate different saccadic targeting patterns during novel word learning compared to typically developing children.

Saccadic targeting during reading is modulated by numerous factors, including word spacing (which shifts the preferred viewing location from word center to word beginning when spaces are absent; Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner, Fischer, & Pollatsek, 1998; Sheridan, Rayner, & Reingold, 2013), word length (longer words elicit initial fixations further from word beginnings and increase refixation probability; Joseph, Liversedge, Blythe, White, & Rayner, 2009; Paterson, Almabruk, McGowan, White, & Jordan, 2015), and morphological structure (complex morphological structures shift initial fixation positions from word center to word ending; Hyönä, Yan, & Vainio, 2018; Yan et al., 2014). Understanding how saccadic targeting is regulated by low-level visual and high-level linguistic information constitutes a fundamental aspect of oculomotor control research and provides empirical basis for refining cognitive models of reading (such as the E-Z Reader model; Reichle, Pollatsek, & Rayner, 2006, and the SWIFT model; Engbert, Nuthmann, Richter, & Kliegl, 2005).

Previous research has demonstrated that Chinese readers dynamically adjust basic saccadic targeting based on target word processing difficulty: greater processing difficulty (e.g., lower frequency, lower predictability, higher visual complexity) results in shorter incoming saccades, initial fixation positions closer to word beginnings, and shorter outgoing saccades. This occurs because increased processing difficulty in the parafovea affects preview efficiency, while increased foveal processing difficulty affects outgoing saccade programming (Liu, Guo, Yu, & Reichle, 2018; Liu, Yu, & Reichle, 2019; Ma & Li, 2015; Perea et al., 2009; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner, Binder, Ashby, & Pollatsek, 2001; Wei, Li, & Pollatsek, 2013; Yan & Kliegl, 2016).

Since novel word learning is a repetitive process requiring multiple contextual exposures to establish and consolidate lexical representations, repeated learning trials progressively strengthen the orthographic, phonological, and semantic connections of novel word morphemes and gradually refine lexical representations (Bai et al., 2019; Blythe et al., 2012; Joseph et al., 2014; Liang et al., 2015, 2017). This implies that processing difficulty actually decreases as familiarity with the novel word’ s form, sound, and meaning increases (Joseph et al., 2014). Does saccadic targeting to novel words adjust accordingly with learning progression?

Research from the temporal perspective has shown that both children with DD and typically developing children exhibit decreasing fixation durations on novel words with increased learning trials, but with different patterns: children with DD show a continuous decline, while typically developing children show a stepwise decline (Blythe et al., 2012; Liang et al., 2015, 2017). These findings suggest that increased learning trials enhance familiarity and reduce processing difficulty, thereby facilitating novel word learning. However, due to cognitive processing deficits in lexical identification (such as morphological awareness deficits and phonological awareness deficits; Ho et al., 2000; Ho et al., 2002; Shu et al., 2006), children with DD show slower decreases in fixation durations, reflecting inefficient novel word learning. Does the effect of learning trials on saccadic targeting during novel word learning differ between children with DD and typically developing children? Our second objective was to investigate whether children with DD show deficits in utilizing learning trials to modulate saccadic targeting during novel word learning.

Using a repeated novel word learning paradigm, we compared eye movement patterns between children with developmental dyslexia (DD) and chronological age-matched controls (CA) during repeated exposures to novel words. We first examined group differences in saccadic targeting during novel word learning, then investigated how learning trials modulated targeting patterns in children with DD. Based on previous research on Chinese reading (Bai et al., 2011; Liu et al., 2015, 2016, 2018; Ma & Li, 2015; Wei et al., 2013; Yan et al., 2016) and the unique challenges of novel word learning, we hypothesized that: (1) Due to the substantial processing difficulty of novel words (Blythe et al., 2012), children with DD would exhibit saccadic targeting deficits during novel word learning, characterized by initial fixation positions closer to word beginnings and shorter incoming saccades compared to controls; (2) Children with DD would demonstrate poorer ability than controls to modulate saccadic targeting using learning trials.

2.2 Experimental Materials

We adopted the experimental materials from Bai et al. (2019). The materials comprised 30 novel words embedded in sentences of 13-14 characters each. Sentence difficulty averaged 4.47 (SD = 0.35) and sentence naturalness averaged

4.31 (SD = 0.29), indicating that sentences were easy to comprehend and fluent. Each novel word was presented in eight sentences that described it as a new member of a familiar semantic category. Ten semantic categories were used: stationery, occupations, flowers, buildings, transportation, clothing, medicine, animals, furniture, and fruits, with three pseudowords per category. For each novel word, 1-3 reading comprehension questions and one semantic category selection question were randomly assigned to assess participants' understanding of sentence meaning and their mastery of the novel word' s semantic category. Example materials are shown in Table 2 .

To reduce fatigue effects, the 30 novel words were divided into two sets of 15 words each, with 120 sentences per set. Each participant read one set. The two material sets did not differ significantly in character frequency, stroke count, morpheme positional probability (first and last characters), average association values of novel words, or sentence naturalness and difficulty (ts < 1.64, ps $>$ 0.05), as shown in Table 3 , confirming material homogeneity.

2.3 Apparatus

An SR Research Eyelink 1000 eye tracker (sampling rate: 1000 Hz) was used with a display resolution of 1024 × 768 pixels and refresh rate of 120 Hz. Viewing distance was 65 cm. Text was presented in 18-point Song font, with each character subtending 25 × 25 pixels (0.74° of horizontal visual angle).

2.4 Procedure

Participants were tested individually. A five-point calibration procedure was conducted with average error less than 0.5°. Participants were instructed to read sentences carefully and press the left mouse button to indicate completion of each sentence, then use mouse clicks to select answers to comprehension and semantic category questions. Each participant learned 15 novel words in two sessions with a 10-minute break between sessions. The entire experiment lasted approximately 45 minutes.

2.5 Interest Area Definition

Novel words were designated as interest areas. Following previous research (Bai et al., 2011; Yan et al., 2010; Zang, Liang, Bai, Yan, & Liversedge, 2013), each novel word was divided into four regions. Fixations falling in regions 1, 2, 3, and 4 were coded as landing positions 0-0.5, 0.5-1, 1-1.5, and 1.5-2, respectively, as shown in Figure 1 [Figure 1: see original paper].

Reading comprehension accuracy was above 80% for both groups (DD: M = 80%; CA: M = 87%), and semantic category selection accuracy was above 95% (DD: M = 95%; CA: M = 99%), indicating that all participants read the sentences attentively and correctly learned the semantic categories after eight contextual exposures. However, DD group performance was significantly lower than the CA group on both measures ($t(32) = 2.32$, $p = 0.027$, $d = 0.82$; $t(26) = 2.06$,

$p = 0.049$, $d = 0.81$), suggesting that children with DD had poorer reading comprehension and semantic inference abilities.

Data were excluded based on the following criteria (Blythe et al., 2012; Joseph et al., 2014; Liang et al., 2015, 2017): (1) sentences with fewer than three fixations (0.88%); (2) lost eye-tracking data (0.05%); and (3) outliers beyond 3 standard deviations (0.4%). In total, 1.33% of data were excluded.

The following eye movement measures were analyzed for the novel word interest area: mean initial fixation landing position and its distribution; initial fixation landing position and distribution for single-fixation cases; initial fixation landing position and distribution for multiple-fixation cases; refixation probability and its distribution; incoming saccade length to novel words; and outgoing saccade length from novel words.

3.1 Homogeneity Test

We examined whether the two material sets were homogeneous by testing whether saccadic targeting patterns differed across material sets for each group. Data were analyzed using linear mixed models (LMM) in R (R Core Team, 2014) with the lme4 package (Bates, Maechler, & Bolker, 2012), with participants and items as crossed random effects. Significance estimates were obtained using Markov-Chain Monte Carlo posterior distributions (Baayen, Davidson, & Bates, 2008). Material set was entered as a fixed effect to test consistency across sets for each group (results in Table 4 ; fixed effects in Table 5). We initially specified maximal random effects structures, simplifying when models failed to converge. Since final results were consistent with the simplest random effects models, we report the simplest models.

No significant differences were found between material sets for either group on the three primary saccadic targeting measures: mean initial fixation position, incoming saccade length, and outgoing saccade length ($ts < 1.86$, $ps > 0.05$). This indicates that eye movement results were homogeneous across material sets. Therefore, data from both sets were combined in subsequent analyses.

3.2 Modulation of Learning Trials on Saccadic Targeting in Children with DD

We examined the effect of learning stage on saccadic targeting by comparing patterns across learning trials. Exposures 1-4 were designated as Learning Stage 1 and exposures 5-8 as Learning Stage 2. Linear mixed models were conducted with group, learning stage, and their interaction as fixed effects. Launch site was included as a covariate because it influences saccadic targeting (Cutter, Drieghe, & Liversedge, 2017; Hyönä et al., 2018).

Saccadic targeting results for both groups across learning stages are presented in Table 6 , with fixed effects analyses in Table 7 .

3.2.1 Mean Initial Fixation Position and Distribution Children with DD showed initial fixation positions closer to word beginnings compared to controls (b = -0.12, SE = 0.06, t = -2.14, p = 0.039). The difference between learning stages was not significant (b = 0.02, SE = 0.02, t = 1.13, p = 0.258), but the group × stage interaction was significant (b = -0.10, SE = 0.03, t = -2.93, p = 0.003). Further analysis revealed no significant difference between learning stages for the DD group (b = 0.03, SE = 0.02, t = 1.10, p = 0.273), whereas control children showed initial fixation positions closer to word centers in Stage 2 compared to Stage 1 (b = -0.07, SE = 0.02, t = -2.95, p = 0.003).

3.2.2 Incoming and Outgoing Saccade Lengths Incoming saccade lengths were significantly shorter for children with DD than controls (b = -0.12, SE = 0.06, t = -2.14, p = 0.039). The main effect of learning stage was not significant (b = 0.02, SE = 0.02, t = 1.13, p = 0.258), but the group × stage interaction was significant (b = -0.10, SE = 0.03, t = -2.93, p = 0.003). Further analysis showed no significant differences between learning stages for either group on incoming saccade length (DD: b = 0.04, SE = 0.04, t = 1.00, p = 0.319; CA: b = -0.04, SE = 0.04, t = -1.10, p = 0.272).

For outgoing saccade length, the group difference was not significant (b = -0.15, SE = 0.16, t = -0.94, p = 0.352). Outgoing saccades were shorter in Stage 1 than Stage 2 (b = 0.17, SE = 0.03, t = 5.18, $p < 0.001$), and the group × stage interaction was marginally significant (b = -0.13, SE = 0.07, t = -1.94, p = 0.052). Both groups showed significantly longer outgoing saccades in Stage 2 (DD: b = -0.13, SE = 0.05, t = -2.72, p = 0.006; CA: b = -0.28, SE = 0.05, t = -5.85, $p < 0.001$), but the increase was smaller for children with DD (mean difference = 0.11) than for controls (mean difference = 0.27).

3.2.3 Refixation Probability Refixation probability did not differ significantly between groups (b = 0.41, SE = 0.24, t = 1.74, p = 0.083). Refixation probability was higher in Stage 1 than Stage 2 (b = -0.56, SE = 0.07, z = -7.52, $p < 0.001$), but the learning stage × group interaction was not significant (b = 0.22, SE = 0.15, z = 1.50, p = 0.133).

In summary, children with DD exhibited saccadic targeting deficits during novel word learning, specifically showing shorter incoming saccade lengths. Both groups showed modulation by learning stage, but with different patterns and magnitudes: Control children demonstrated increased outgoing saccade lengths, initial fixation positions closer to word centers, and lower refixation probabilities with increased learning trials. Children with DD showed increased outgoing saccade lengths (though to a lesser degree than controls) and lower refixation probabilities, but showed no modulation of incoming saccade lengths.

4. Discussion

This study examined saccadic targeting differences between children with DD and chronological age-matched controls during novel word learning, and investigated how learning stage modulated targeting patterns in both groups. The findings revealed: (1) Children with DD showed saccadic targeting deficits during novel word learning, specifically shorter incoming saccade lengths compared to controls; (2) Both groups showed modulation by learning trials, but the effects differed: for controls, increased learning trials affected both outgoing saccade lengths and mean initial fixation positions, whereas for children with DD, effects were limited to outgoing saccade lengths. We discuss these results in relation to the cognitive deficits associated with DD and the mechanisms underlying saccadic targeting.

4.1 Saccadic Targeting Deficits in Children with DD During Novel Word Learning

In Chinese reading, saccadic targeting is determined by both parafoveal and foveal processing of target words (Liu et al., 2015, 2016, 2018; Wei et al., 2013; Yan et al., 2009, 2010, 2016). Mean initial fixation position and incoming saccade length primarily reflect parafoveal processing efficiency, while outgoing saccade length primarily reflects foveal processing efficiency (Liu et al., 2015, 2016; Yan et al., 2010, 2016). Our findings that children with DD showed higher refixation probabilities and shorter incoming saccades indicate inefficient saccadic targeting during novel word learning, likely resulting from reduced parafoveal preview efficiency. Several factors may contribute to this deficit:

First, children with DD have reduced perceptual spans, limiting their ability to preview complete novel word information in the parafovea (Xiong, 2014; Yan et al., 2010). Xiong (2014) found that Chinese children with DD have perceptual spans limited to 1-2 characters to the right of fixation, substantially smaller than age-matched controls (3 characters to the right). Pan, Yan, Laubrock, Shu, and Kliegl (2014) also found that children with DD showed landing position deficits, with single fixations landing closer to word beginnings when processing two- and three-character words. Since our novel words were all two-character items, children with DD may have only been able to preview the first character parafoveally, preventing them from adjusting saccadic targeting based on word length as effectively as controls.

Second, the children with DD in our study exhibited deficits in orthographic processing, phonological processing, automatic orthography-phonology conversion, and reading fluency (Ho et al., 2000; Ho et al., 2002; Meng et al., 2011; Yan, Pan, Laubrock, Kliegl, & Shu, 2013). These deficits in Chinese character processing may have caused them to: (1) expend more cognitive resources on foveal processing, leaving fewer resources for parafoveal preview (Yan et al., 2013); and (2) reduce the effectiveness of obtaining orthographic and phonological information from parafoveal previews of novel words. Consequently, they may have adopted a more conservative saccade-targeting strategy—shortening saccade lengths and landing initial fixations near word beginnings—to enable refixations and multiple processing attempts, thereby maintaining reading efficiency.

It is important to note that because children with DD in our study had significantly lower character recognition than controls, we used sentences appropriate for third-grade reading level (matched to the reading ability of children with DD) to ensure that fifth-grade children with DD could recognize all characters and avoid confounding effects of limited character knowledge on novel word learning efficiency.

Interestingly, we found no group difference in outgoing saccade length, suggesting equivalent foveal processing efficiency for novel words. Combined with Bai et al.' s (2019) finding that children with DD require longer processing times for foveal novel word processing, this suggests that processing inefficiency in DD may be primarily manifested in the temporal ("when") rather than spatial ("where") domain. This may reflect ceiling effects: because novel words resemble extremely low-frequency items, both children with DD and controls may expend maximal cognitive resources on foveal processing, leaving minimal resources for parafoveal processing of subsequent words and thus eliminating group differences in outgoing saccade lengths.

4.2 Modulation of Learning Stage on Saccadic Targeting in Children with DD

In Chinese reading, target word processing difficulty influences saccadic targeting: greater difficulty (e.g., lower frequency, lower predictability, higher visual complexity) produces shorter incoming saccades, initial fixations closer to word beginnings (due to increased parafoveal processing difficulty), and shorter outgoing saccades (due to increased foveal processing difficulty; Liu et al., 2015, 2016, 2018; Ma & Li, 2015; Wei et al., 2013; Yan et al., 2010, 2016). Our results showed that with increased learning trials, control children shifted initial fixation positions toward word centers and increased outgoing saccade lengths, indicating that accumulated familiarity strengthened form-sound-meaning connections, reduced parafoveal preview difficulty and foveal processing demands, and facilitated saccadic targeting.

However, for children with DD: (1) Increased learning trials produced smaller increases in outgoing saccade lengths compared to controls. While learning trials enhanced familiarity and likely facilitated the familiarity-check stage of lexical access (Reichle et al., 2006), children with DD may have deficits in saccade error adjustment and adaptation (Freedman, Molholm, Gray, Belyusar, & Foxe, 2017), preventing them from rapidly and effectively adjusting saccades to intended landing positions during the saccade programming stage. Consequently, they showed reduced benefits from learning trials. (2) Learning trials did not affect incoming saccade lengths or mean initial fixation positions in children with DD, indicating they could not utilize increased familiarity to enhance parafoveal processing efficiency and modulate incoming saccades as controls did. This may reflect that, compared to controls, children with DD have lower lexical identification efficiency (Bai et al., 2019), requiring them to allocate substantial cognitive resources to foveal processing while allocating fewer resources to parafoveal processing. Thus, even after repeated exposures, they could not improve parafoveal preview efficiency for difficult novel words and showed no learning-related benefits.

4.3 Conclusions

Under the conditions of this study, we conclude that: (1) Children with developmental dyslexia exhibit saccadic targeting deficits during novel word learning, specifically shorter incoming saccade lengths and initial fixation positions in multiple-fixation cases that land closer to word beginnings; (2) Children with developmental dyslexia show deficits in utilizing learning trials to modulate saccadic targeting during novel word learning, as they cannot effectively adjust incoming saccade lengths and mean initial fixation positions with increased learning trials.

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